10

Operational Amplifiers

10.1 What are operational amplifiers?

Operational amplifiers are active components that can be used to amplify signals in electrical circuitry (e.g. amplification of a signal that your mobile telephone received on its antenna). An operational amplifier (or opamp in short) usually has two inputs and one output. Furthermore, connections for the positive and negative supply voltages (V_+ and V_-, respectively), are present. The output voltage of the opamp V_{out} can be written as a function of the potential difference between the positive and negative input potentials (V_{in+} and V_{in-}, respectively):

$$V_{out} = G \cdot (V_{in+} - V_{in-}) \tag{10.1}$$

where G is the amplification. When no other components are connected, G is in the order of 100.000 to 1.000.000! However, although the gain is very high, the output voltage is limited by the positive and negative supply voltages. When the output voltage reaches one of these limits while Equation 10.1 states that it should be higher (or lower), we say that the opamp is clipping.

A schematic symbol for an opamp is given in Figure 10.1. You will see that the positive and negative supply voltage pins are often omitted.

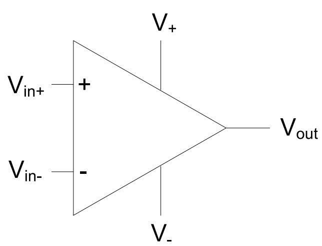


Figure 10.1: *Schematic symbol for an operational amplifier.*

In most applications, opamps are used in configurations with a negative feedback connection. This means that the output of the opamp is connected to the negative input, either directly or by means of extra components. You may ask yourself why one would connect an opamp in this way. To understand this, we recall the high gain of the (plain) opamp. Due to the high gain, small potential differences between the input pins (e.g. millivolts) already result a clipping opamp. However, when we connect the negative input to the output, the total gain will become smaller and we get a different situation. In Figure 10.2 an opamp with a negative feedback configuration is given. The feedback is achieved using a resistor.

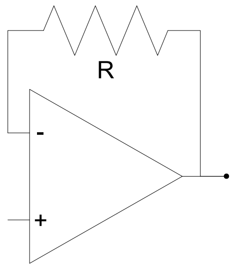


Figure 10.2: *Operational amplifier with in a negative feedback configuration using a resistor.*

First, we distinguish between the following three cases:

1. $V_{in+} > V_{in-}$;
2. $V_{in+} < V_{in-}$;
3. $V_{in+} = V_{in-}$.

Next, we assume that the inputs have an infinitely high impedance, so no current will flow into the inputs. When $V_{in+} > V_{in-}$, a high output voltage creates an increase of the negative input due to this feedback resistor. This may result in the second case. In this case a low output voltage decreases the negative input. Eventually, the effect of both cases result in the third case. In other words, the negative feedback forces the potential difference on the input to 0 V. Therefore, when using such configurations, we may assume the negative input potential equal to the positive input potential.

We can conclude that, for ideal opamps with a negative feedback loop, we have two important premises:

1. No current will flow into the inputs;
2. The negative feedback reduces the potential difference on the input to 0 V.

Exercise 10.1

We have a voltage divider with its output connected to the positive input of an opamp whose output is directly connected to its negative input. Such a configuration is called a buffer. Reason why we would want such a configuration.

Hint: the opamp has a high input impedance and a low output impedance.

10.2 Application

10.2.1 Opamps and inverting amplifiers

An opamp can be used for an inverting amplifier. We call the amplifier inverting because the output signal is an amplified version of the input signal with an altered sign. In Figure 10.3 a circuit of an inverting amplifier is given.

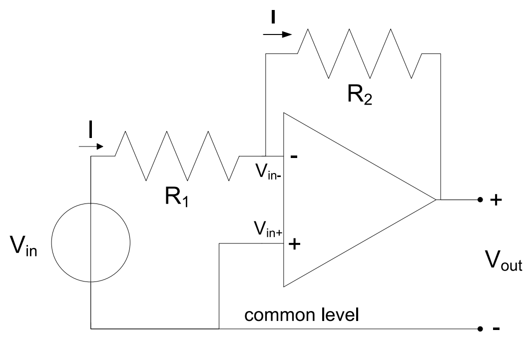


Figure 10.3: *Operational amplifier used in an inverting amplifier circuit.*

The transfer of this circuit (i.e. $\frac{V_{out}}{V_{in}}$; the gain of the amplifier), can be determined in three steps:

1. V_{in} = I. R_1; remember V$_{in-}$ = V_{in+} and so V_{in-} is at 0 V level.
2. Because the current cannot flow into the input, it flows through resistor R_2. With $V_{in-} = V_{in+}$, $V_{out} = 0 - I \cdot R_2$;
3. Rewrite the value for V_{out} in terms of V_{in} and find $V_{out} = -\frac{R_2}{R_1} \cdot V_{in}$.

For the inverting amplifier circuit drawn in Figure 10.3 we thus have the following transfer:

$$V_{out} = -\frac{R_2}{R_1} V_{in} \tag{10.2}$$

By choosing the right resistance values, we can thus realize every gain we want. For example, if a gain of 10 is needed, we can use $R_1 = 1$ kΩ and $R_2 = 10$ kΩ. Note that when $R_2 < R_1$ we have an inverted attenuator.

10.2.2 Opamps and non-inverting amplifiers

Often it is not wanted to invert a signal when it is amplified. If this is the case, you can use the opamp in a non-inverting amplifier circuit. An example of such a circuit is drawn in Figure 10.4.

For the non-inverting amplifier circuit drawn in Figure 10.4, we have the following transfer:

$$V_{out} = (1 + \frac{R_2}{R_1}) V_{in} \tag{10.3}$$

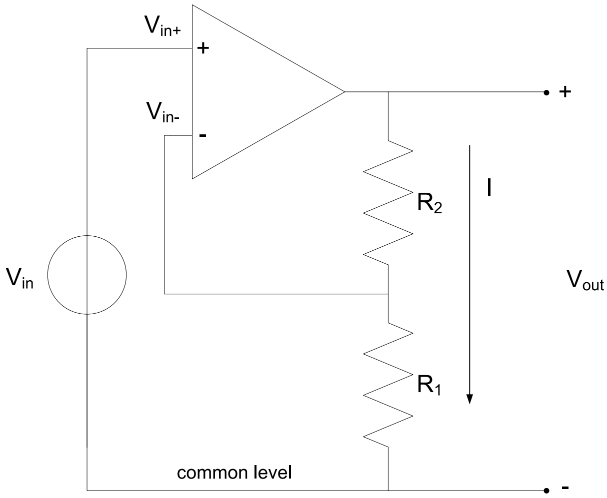


Figure 10.4: *Operational amplifier used in a n on-inverting amplifier circuit.*

? Question 10.1

Determine (the same way as we did for the inverting amplifier) that for the transfer of the non-inverting amplifier, drawn in Figure 10.4, holds:

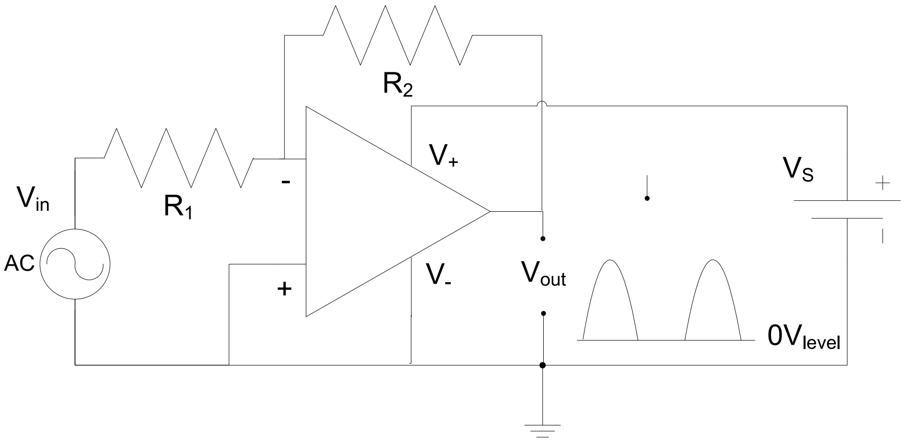
$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1}$$

Hint: use the fact that in fact V_{in-} is the output voltage of the voltage divider that divides the output voltage V_{out}.

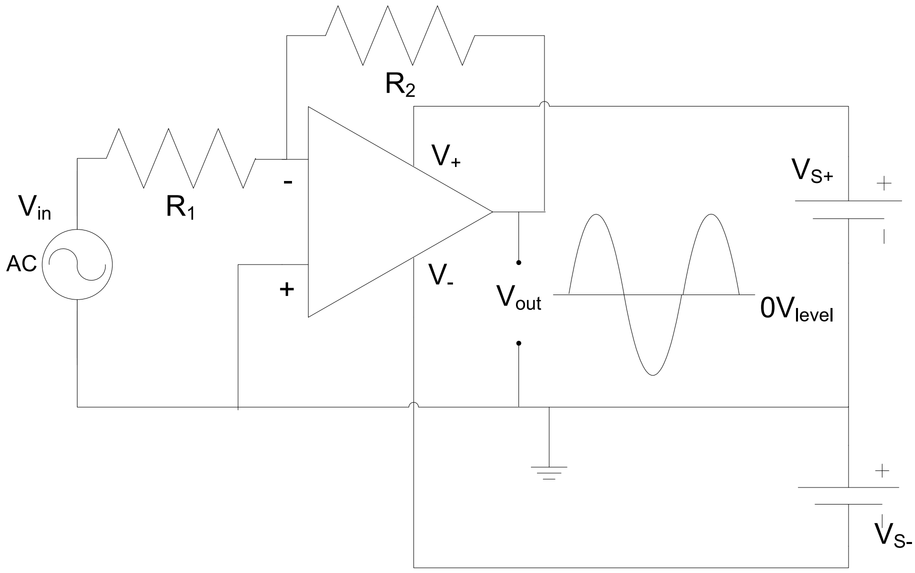
! Note

The discussed operational amplifiers are supposed to be ideal. However, in practice, there are several limitations:

- the output cannot be regarded being an ideal voltage source. the output impedance Z_{out} is in general low (a few hundred Ohm) and depends on the amount of negative feedback applied.
- the output current I_{out} is limited and thus the power that the opamp can deliver is limited.
- the output can saturate to the positive and negative supply voltages so it cannot be driven to these voltages completely;
- when choosing the wrong component values, a significant part of the output power may be lost in the feedback network. So the feedback resistors R_1 and R_2 have to be chosen in $\mathbf{k}\Omega$'s or $\mathbf{M}\Omega$'s. A suitable range would be: $> 1\mathbf{k}\Omega < 10\mathbf{M}\Omega$.
- for amplifying AC signals you will often need to apply a so-called symmetrical power supply for 'feeding' the opamp. See figure: 10.5



Inverting AC amplifier – single power supply applied



Inverting AC amplifier – symmetrical (Vs+ = Vs-) power supply applied

Figure 10.5: *Operational amplifier used as AC amplifier.*

The significance of these limitations depends on the specific type of opamp and on the configuration in which it is used. The data sheet will provide you with the parameters needed to make a good choice of which opamp to use.

10.2.3 Opamps and comparators

Clipping amplifiers are not always a problem. Moreover, at times this behavior is wanted. For example, if you compare two values and the only thing you need to know is whether value 1 is higher than value 2, such behavior is ideal! Circuits that perform the comparison are called comparators. In Figure 10.6 a typical comparator circuit is shown. Instead of the voltage division using two resistors, you can also use a potmeter!

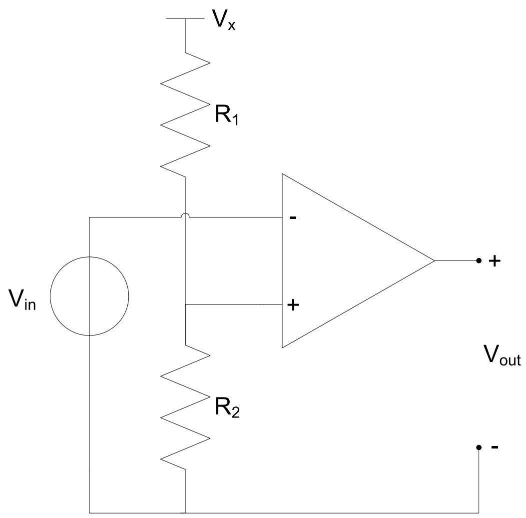


Figure 10.6: *Operational amplifier used in a comparator circuit with static comparison.*

The output voltage of the circuit shown in Figure 10.6 is equal to the positive supply voltage whenever $V_{in} < \frac{R_1}{R_1+R_2} \cdot V_x$ and equal to the negative supply voltage in the other cases.

Although the discussed circuit works as expected, in most cases it is not usable. Take for example an input signal that is very noisy. Around the 'decision level', this will result in a toggling output value, as depicted in Figure 10.7.

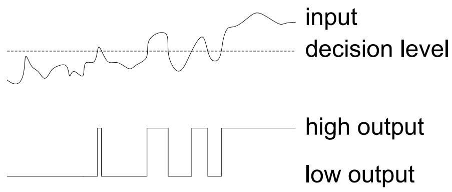


Figure 10.7: *The output of a comparator toggles when the input is noisy.*

To overcome the problem of the toggling output, a solution called hysteresis can be used. With this solution, the decision levels for increasing input values and decreasing input values are not the same. This is depicted in Figure 10.8.

When the input increases above the level at which the output switches from high to low, small decreases in the input do not result in an output switch from low to high. Similarly, when the input decreases below the level at which the output switches from low to high, small increases in the input do not result in an output switch from high to low.

Hysteresis can be implemented using an opamp with a positive feedback loop, which is also known as feedforward. Instead of connecting the output with the negative input, the output is now connected with a resistor to the positive input. A comparator circuit with feedforward is drawn in Figure 10.9.

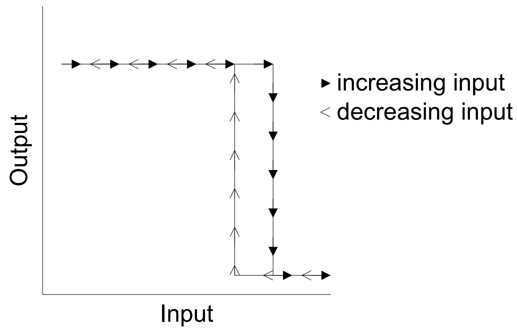


Figure 10.8: *Hysteresis.*

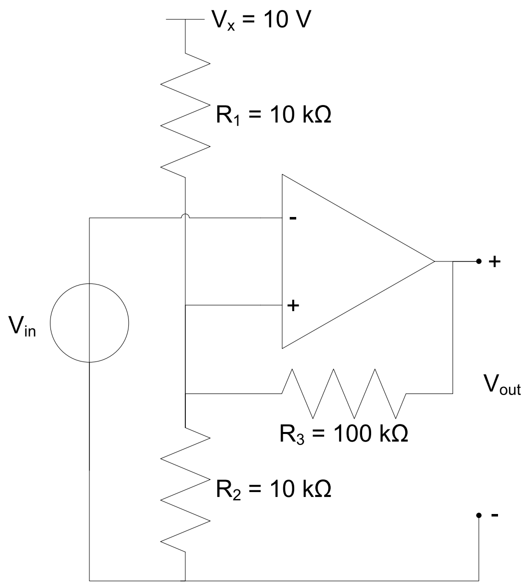


Figure 10.9: *An opamp with feedforward in a static comparator circuit.*

To simplify calculations, we take the resistance value of resistors R_1 and R_2 10 kΩ, the resistance value of resistor R_3 100 kΩ, V_x equal to $V_{out,high} = V_+ = 10V$, and $V_{out,low} = V_- = 0$ V. We can now distinguish between two cases.

Case 1: $V_{out} = 10$ V.
The resulting circuit is given in Figure 10.10(a). Since resistors R_1 and R_3 have the same voltage drop across them and are connected to the same node, they are connected in parallel. Then remains that V_{in+} is a partial voltage of V_{out}: $V_{in+} = \frac{R_2}{R_2 + \frac{R_1 \cdot R_3}{R_1 + R_3}} \cdot V_x$. After substituting the given values, it follows that $V_{in+} = 5.24$ V.

Case 2: $V_{out} = 0$ V.
The resulting circuit is given in Figure 10.10(b). Since resistors R_2 and R_3 have the same voltage drop across them and are connected to the same node, they are connected in parallel. Then remains that V_{in+} is a partial voltage of V_{out}: $V_{in+} = \frac{\frac{R_2 \cdot R_3}{R_2 + R_3}}{R_1 + \frac{R_2 \cdot R_3}{R_2 + R_3}} \cdot V_x$. After substituting the given values, it follows that $V_{in+} = 4.76$ V.

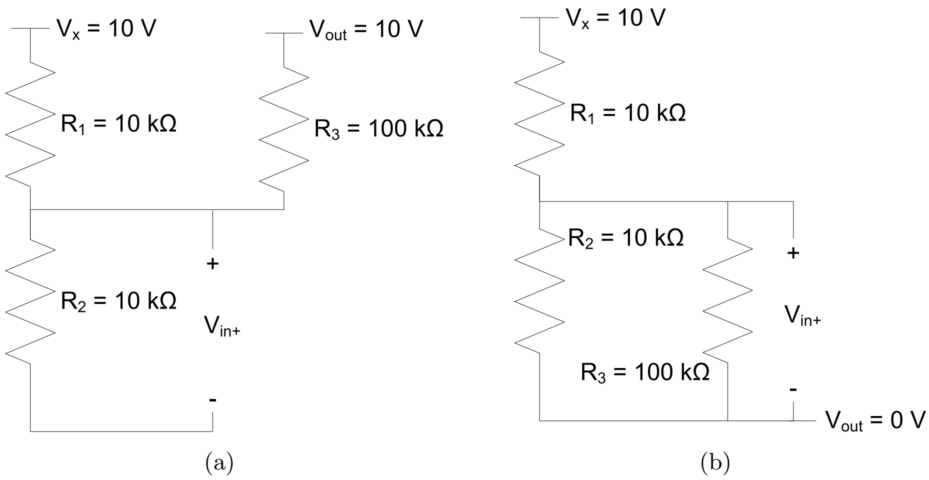


Figure 10.10: *Resulting circuits for (a)* $V_{out} = 10$ *V and (b)* $V_{out} = 0$ *V.*

Like indicated in Figure 10.8, we thus have two different transition levels and the transition level from low to high is lower than the transition level from high to low. For a noisy input signal, the output of the circuit drawn in Figure 10.9 is drawn in Figure 10.11.

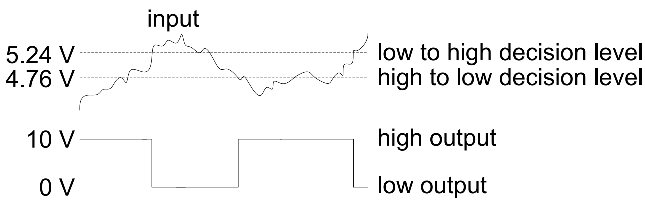


Figure 10.11: *The output of a comparator with feedforward does not make the output toggle for noisy input signals.*

Note that the resistance values of R_1, R_2, R_3 determine the transition levels. When you design a circuit, you should decide whether the circuit needs to be very accurate in decision making or whether there is very much noise present in the input signal.